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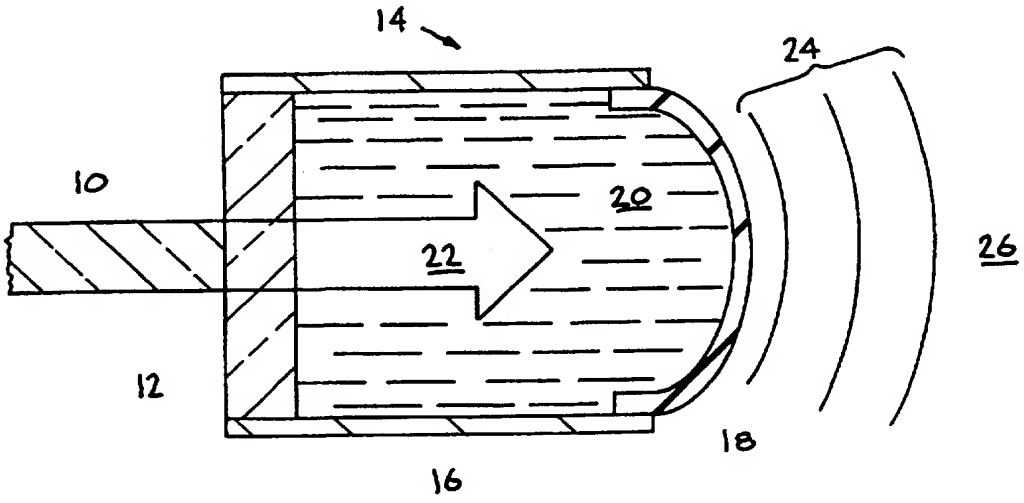

(57) Abstract

This invention is an optically activated transducer (14) for generating acoustic vibrations in a biological medium. The transducer is located at the end of a fiber optic (10) which may be located within a catheter. Energy for operating the transducer is provided optically by laser light transmitted through the fiber optic to the transducer. Pulsed laser light is absorbed in the working fluid (20) of the transducer to generate a thermal pressure and consequent adiabatic expansion of the transducer head such that it does work against the ambient medium. The transducer returns to its original state by a process of thermal cooling. The motion of the transducer within the ambient medium couples acoustic energy (24) into the medium. By pulsing the laser at a high repetition rate (which may vary from CW to 100 kHz) an ultrasonic radiation field can be established locally in the medium. This method of producing ultrasonic vibrations can be used in vivo for the treatment of stroke-related conditions in humans, particularly for dissolving thrombus. The catheter may also incorporate anti-thrombolytic drug treatments as an adjunct therapy and it may be operated in conjunction with ultrasonic detection equipment for imaging and feedback control.

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OPTO-ACOUSTIC TRANSDUCER FOR MEDICAL APPLICATIONS

The United States Government has rights in this invention pursuant to Contract No. W-7405-ENG-48 between the United States Department of Energy and the University of California for the operation of Lawrence Livermore National Laboratory.

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to the removal of blockages in tubular tissues and organs, and more specifically, it relates to the use of a light stimulated opto-acoustic transducer located at the end of a fiber optic within a catheter for use in ultrasound thrombolysis and angioplasty.

Description of Related Art

Ischemic strokes are caused by the formation or lodging of thrombus in the arterial network supplying the brain. Typically these occlusions are found in the carotid artery or even smaller vessels located still higher in the cranial cavity. Interventional cardiologists and vascular surgeons have devised minimally invasive procedures for treating these conditions in the vasculature elsewhere in the body. Among these treatments is ultrasound angioplasty whereby a microcatheter is directed to the site of an occlusion. An ultrasonic transducer is coupled to a transmission medium that passes within the catheter and transmits vibrations to a working tip at the distal end in close proximity to the occlusion. Ultrasonic catheters for dissolving atherosclerotic plaque and for facilitating clot lysis have been described previously. Improvements on these inventions have concentrated on improving the operation or function of the same basic device (Pflueger et al., U.S. Patent No. 5,397,301). The vibrations coupled into the tissues help to dissolve or emulsify the clot through various ultrasonic mechanisms such as cavitation bubbles and microjets which expose the clot to strong localized shear and tensile

stresses. These prior art devices are usually operated in conjunction with a thrombolytic drug and/or a radiographic contrast agent to facilitate visualization.

The ultrasonic catheter devices all have a common configuration in which the source of the vibrations (the transducer) is external to the catheter. The vibrational energy is coupled into the proximal end of the catheter and transmitted down the length of the catheter through a wire that can transmit the sound waves. There are associated disadvantages with this configuration: loss of energy through bends and curves with concomitant heating of the tissues in proximity; the devices are not small enough to be used for treatment of stroke and are difficult to scale to smaller sizes; it is difficult to assess or control dosimetry because of the unknown and varying coupling efficiency between the ultrasound generator and the distal end of the catheter. Dubrul et al., U.S. Patent No. 5,380,273, attempts to improve on the prior art devices by incorporating advanced materials into the transmission member. Placement of the ultrasonic transducer itself at the distal end of the catheter has been impractical for a number of reasons including size constraints and power requirements.

A related method for removing occlusions is laser angioplasty in which laser light is directed down an optical fiber to impinge directly on the occluding material. Laser angioplasty devices have been found to cause damage to or destruction of the surrounding tissues. In some cases uncontrolled heating has lead to vessel perforation. The use of high energy laser pulses at a low or moderate repetition rate, e.g. around 1 Hz to 100 Hz, results in non-discriminatory stress waves that significantly damage healthy tissue and/or result in insufficient target-tissue removal when the independent laser parameters are adjusted such that healthy tissue is not affected. Use of high energy laser light to avoid thermal heating has been found to cause damage through other mechanisms that puncture or otherwise adversely affect the tissue.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide an opto-acoustic transducer located at the end of a fiber optic within a catheter

for use in the removal of either partial or complete vascular blockage, or other luminal occlusions.

The invention has uses in therapeutic applications of angioplasty and thrombolysis. Angioplasty is the removal of atherosclerotic plaque and thrombolysis is the removal of soft clots which are typical in the brain and in the coronary arteries. The problems of energy transmission through the catheter are addressed by using an optical fiber to guide laser pulses to the distal end. Unlike laser angioplasty or laser thrombolysis, direct ablation of the occlusion is not attempted; rather, a high frequency train of small laser pulses is used as an energy source for a miniature ultrasonic transducer. This transducer can be used in a similar fashion to the prior art catheter-based ultrasonic devices. Dissolution of the occlusion is then promoted by the ultrasonic action, and not directly by the interaction with the laser light.

The use of optical energy to induce an ultrasonic excitation in the transducer offers a number of advantages. Most importantly, it can be implemented through a 2.5 French or smaller catheter, such as is required for accessing clots in the cerebrovasculature. Optical fibers can be fabricated to small dimensions, yet are highly transparent and capable of delivering substantial optical power densities from the source to the delivery site with little or no attenuation. The opto-acoustic transducer provides for variable energy delivery by means of independent control over light delivery/working fluid coupling. The working fluid is a substance contained within the transducer which absorbs the optical energy. Engineering design parameters include optical wavelength, optical energy, light pulse duration, light pulse repetition frequency, light pulse duty cycle, fiber dimensions, fiber materials, scattering and absorption of the optical energy in the working fluid, and the thermodynamic parameters of the working fluid. The additional engineering of the mechanical transducer head results in acoustic energy of appropriate magnitude and frequency such that targeted occlusions are preferentially damaged while healthy tissues remain intact or otherwise minimally affected. The present invention will allow delivery of sufficient energy to generate

acoustic excitation through a small and flexible catheter, such as is required for stroke treatment.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows an embodiment of the opto-acoustic transducer of the present invention.

Figure 2 shows a possible thermodynamic cycle of the opto-acoustic transducer.

Figure 3 shows an embodiment of the opto-acoustic transducer in an endovascular catheter.

Figure 4 shows an embodiment of the invention using a bellows head.

Figure 5 shows an embodiment of the invention using a nozzle.

Figure 6 shows an embodiment of the invention using a cantilever-type device.

Figure 7 shows an embodiment of the invention using a microchannel device for converting optical to thermal energy.

DETAILED DESCRIPTION OF THE INVENTION

The invention is a laser light stimulated opto-acoustic transducer operatively located at the end of a fiber optic, for use in ultrasound thrombolysis and angioplasty. The fiber optic may be located within a catheter. The transducer converts pulsed optical energy to acoustic energy in a liquid ambient medium. The pulsed optical energy is most conveniently provided by a laser source operating at the desired repetition rate. The laser wavelength can be chosen to operate anywhere from 200 nm to 5000 nm such that the wavelength can be transmitted efficiently through the fiber optic. Pulse energy density may vary from 0.01 J/cm^2 to 4 J/cm^2 (or up to 50 J/cm^2, if dictated by a small optical fiber diameter), pulse duration from 3 ns to 1 μs, and pulse frequency, or repetition rate may vary from 10 Hz to 100 kHz. Alternately, a lower end of the pulse frequency range may be 100, 200, 400 or 800 Hz, with an upper end of the range being 25, 50 or 100 kHz. The energy applied is maintained below 5 milli-Joules, and preferably less than one milli-Joule. Referring to Figure 1, the opto-acoustic transducer comprises a fiber optic 10 (plastic or glass) which terminates at an optional transparent

window 12 of the transducer 14, which consists of a rigid container 16, a flexible membrane 18 and a working fluid 20. In some embodiments, the fiber itself can act as the transparent window, such that the container is formed around the fiber tip. The cylinder may comprise a high thermal conductivity, e.g., greater than 200 W/m-K, such as can be fabricated with metal alloys or with diamond (2000 W/m-K).

Figure 1 shows the delivery of pulsed optical energy 22 from fiber optic 10 through the transparent window 12 into the working fluid 20 to produce acoustic waves 24 in an ambient medium 26. The range of the acoustic waves can be from continuous wave (CW) to 100 kHz. The transparent window 12, rigid container 16 and flexible membrane 18 together define a confined volume. Flexible membrane 18 will allow expansions and contractions of the working fluid within the confined volume to be transmitted to an external medium (such as the ambient medium 26). Transparent window 12 may comprise glass, sapphire, diamond or quartz, and may be used for the protection of plastic fibers from acoustic damage. The transparent window allows transmission of pulsed optical energy to be absorbed by the working fluid 20 contained within the structure. The window can be attached to the fiber tip with a suitable optical cement or epoxy adhesive. An additional element (not shown in Figure 1), consisting of a rigid structure possessing an open structure (holes or channels) or a porous structure may be placed in the volume to facilitate absorption of the laser energy and shorten the thermal relaxation time constant of the system while providing space for containing the working fluid.

The opto-acoustic transducer of the present invention operates on thermodynamic principles similar to those describing the thermodynamics of a heat engine. Figure 2 is a diagram of a possible thermodynamic path of the working fluid contained within the transducer volume. For the purposes of explanation, the transducer operation is described based on this particular example, although other thermodynamic cycles may be possible depending on the parameters of the particular device. The thermodynamic path maps out a cycle on the PV plane, where P is the fluid pressure, and V is the

fluid specific volume. In this example, the inertial response time of the transducer coupled to the ambient medium is assumed to be long compared to the laser pulse duration, and short compared to the thermal relaxation time of the device. The cycle begins at point A on the diagram where the working fluid is in equilibrium with the ambient pressure and temperature. When a short pulse of optical energy is absorbed in the working fluid, the internal energy is increased and the fluid is heated (A to B). As a consequence of this heating, the fluid temperature is raised, and also the fluid pressure. The force of the fluid pressure against the membrane causes expansion of the fluid (B to C) and motion of the transducer membrane into the ambient fluid. This process takes place adiabatically on a time scale shorter than the thermal relaxation time of the transducer within the ambient medium. In the third phase of the cycle, the heated fluid relaxes to the temperature of the ambient medium as the energy deposited in the transducer is carried off by thermal conduction to the ambient medium (C to A). The net mechanical work done on the ambient fluid during this cycle is represented by the area contained in the triangle bounded by the process cycle. This idealized cycle does not take into account irreversible loss mechanisms.

Figure 3 shows an embodiment of the opto-acoustic transducer in an endovascular catheter. Catheter 30 is located within a blood vessel 32 near an occlusion 34. An adjunct fluid delivery tube 35 and an optical fiber 36 with an opto-acoustic transducer 38 are located within catheter 30. The figure depicts the generation of ultrasonic vibration waves 40 by opto-acoustic transducer 38 to break up the occlusion 34. As an aid to the process, an adjunct fluid 42 is delivered to the occlusion 34. The adjunct fluid is a thrombolytic fluid or agent.

A particular embodiment of the present invention comprises, for example, a 400 μm diameter optical fiber, a titanium cylinder of appropriate size attached to the end of the fiber, a working fluid filling the cylinder cavity, and an elastic membrane attached to the end of the cylinder opposite the fiber to form a seal. The elastic membrane is filled with the working fluid, then placed over the fiber

tip and attached. The working fluid contained in the transducer can be dyed water, saline or an inert fluid with low critical temperature, such as a chloro-fluorocarbon fluid (e.g. C_6F_{12}) with critical point temperatures in the range of 250 K to 450 K. The optical fiber is coupled at the proximal end to a high repetition rate laser system which injects pulses of light into the fiber. The light emerging from the fiber at the distal end is absorbed by the working fluid contained in the transducer. The optical fiber functions primarily as a means of energy transmission such that the optical energy produced by the laser is delivered to the transducer with little or no loss.

A bellows-type opto-acoustic transducer head, shown in Figure 4 has a light-absorbing fluid 50 contained within a bellows head 52, and the transducer is attached over the tip 54 of fiber optic 56. Light from the laser source is absorbed by the entrapped fluid 50, the fluid vaporizes causing a pressure rise, and the bellows expands axially, impinging on the clot or plaque. In one embodiment, dimensions of the invention in inches include (i) a fiber diameter of .041, (ii) a bellows assembly length of .252, (iii) a bellows tip of .103, (iv) a bellows diameter of .061 and (v) a bellows wall thickness of .002. The advantages of this type of device include: directed motion of the pressure wave, it does not use blood for energy absorption, and the transducer may be excited in a resonant mode, increasing the amount of axial motion. In the resonant mode, when the pulses of laser energy are transmitted at the proper frequency (resonant frequency) the amplitude of motion of the transducer head will be significantly larger than at other frequencies. Alternatively, at this frequency significantly less laser energy will be needed to achieve a given displacement. The resonant frequency can be adjusted by varying the stiffness of the transducer. The bellows transducer 52 is made by precision machining a mandrel such that it has the desired internal dimensions of the transducer. The transducer head can be made of any bio-compatible metal which can be electroplated or electrodeless plated, such as platinum or gold. Non-bio-compatible metals such as copper or nickel may be used if they are coated with a bio-compatible layer. The metal is plated over the mandrel to the desired thickness,

e.g. 10 μm-100 μm, and the mandrel is selectively dissolved away using a wet chemical etchant, leaving the hollow transducer.

Nozzles for placement at the fiber tip 60 have also been fabricated, as shown in Figure 5. This will serve to increase the velocity of the fluid flow (e.g., blood) away from the catheter tip, and to direct the fluid flow in the axial direction. Also, the fluid flow could be directed obliquely, including perpendicular, to the fiber axis with one or more holes through the side of the nozzle 62. The nozzle can use blood or perfused saline as the working fluid. Adjunct therapy also can be used with the nozzle. Nozzles are fabricated using conventional machining of metals or plastics, injection molding, and electroforming (bellows process).

Figure 6 shows a spring-type device. A fiber optic 70 with a rigid container 72 located at its distal end 74 has a suspended tip 76 which covers the open end of rigid container 72. The tip 76 is not attached all the way around the open end of rigid container 72; rather, it is attached by a suspension which allows it to deflect outwards from the end of container 72. The tip may be formed of silicon, may be flat or, as shown in the Figure, may have a shape formed thereon to increase the ability of the device to exert force on a blockage. When inserted into a blood sample or blood filled vasculature, blood seeps through the unconnected portion of the suspended tip or cantilever, and fills the volume defined by the rigid container 72, the distal end 74 of the fiber 70 and the cantilever or suspended tip 76. Upon operation, a laser pulse initiates a thermodynamic cycle in the blood within the confined volume which actuates the tip 76. Alternatively, saline or other fluid can be continuously introduced into the cavity for use as the working fluid.

Figure 7 shows a microchannel device. This device comprises a microchannel element 80 located at the distal end of fiber optic 82. The side 86 of microchannel element 80 that is facing the laser radiation source (shown as block 88) comprises fine pitched microchannels or another laser radiation trapping or absorbing surface. The side 90 of microchannel element 80 that is facing the fluid (shown as block 92) comprises a microchannel structure to increase the surface area and to enhance the thermal transfer from

the laser radiation source 88 to the fluid 92. The microchannels are fabricated by anisotropically etching a {110}-oriented single crystal of silicon using silicon nitride as a masking layer. Standard photolithographic techniques are used to pattern the silicon nitride, and the silicon is etched using a solution of potassium hydroxide in water. As an alternative to microchannels, a porous silicon structure can be used. Porous silicon is fabricated using an electrochemical hydrofluoric acid etch of a single crystal of silicon.

Applications envisioned for this invention include any method or procedure whereby localized ultrasonic excitations are to be produced in the body using a catheter system for guidance and delivery. The invention may be used in (i) endovascular treatment of vascular occlusions that lead to ischemic stroke (This technology can lyse thrombus and lead to reperfusion of the affected cerebral tissue), (ii) endovascular treatment of cerebral vasospasm (This technology can relax vaso-constriction leading to restoration of normal perfusion and therefore prevent further transient ischemic attacks or other abnormal perfusion situations), (iii) endovascular treatment of cardiovascular occlusions (This technology can lyse thrombus or remove atherosclerotic plaque from arteries), (iv) endovascular treatment of stenoses of the carotid arteries, (v) endovascular treatment of stenoses of peripheral arteries, (vi) general restoration of patency in any of the body's luminal passageways wherein access can be facilitated via percutaneous insertion, (vii) any ultrasonic imaging application where a localized (point) source of ultrasonic excitation is needed within an organ or tissue location accessible through insertion of a catheter, (viii) lithotriptic applications including therapeutic removal of gallstones, kidney stones or other calcified objects in the body and (ix) as a source of ultrasound in ultrasound modulated optical tomography.

The pulsed laser energy source used by this invention can be based on a gaseous, liquid or solid state medium. Rare earth-doped solid state lasers, ruby lasers, alexandrite lasers, Nd:YAG lasers and Ho:YLF lasers are all examples of lasers that can be operated in a pulsed mode at high repetition rate and used in the present invention. Any of these solid state lasers may incorporate non-linear

frequency-doubling or frequency-tripling crystals to produce harmonics of the fundamental lasing wavelength. A solid state laser producing a coherent beam of visible or ultraviolet radiation may be employed directly with the invention or used in conjunction with a dye laser to produce an output beam which is tunable over a wide portion of the ultraviolet and visible spectrum. Tunability over a wide spectrum provides a broad range of flexibility for matching the laser wavelength to the absorption characteristics of the working fluid contained in the transducer. The output beam is coupled by an optical fiber to the acousto-optic transducer at the surgical site through, for example, a percutaneous catheter. In operation, a pulsed beam of light actuates the transducer which removes and/or emulsifies thrombus or atherosclerotic plaque with less damage to the underlying tissue and less chance of perforating the blood vessel wall than prior art devices.

Various other pulsed lasers can be substituted for the disclosed laser sources. Similarly, various dye materials can be used in the dye laser. Configurations other than a free-flowing dye , such as dye-impregnated plastic films or cuvette-encased dyes, can be substituted in the dye laser. The dye laser can also store a plurality of different dyes and substitute one for another automatically in response to user-initiated control signals or conditions encountered during use (e.g. when switching from a blood-filled field to a saline field or in response to calcific deposits). Suitable dyes for use in the dye laser components of the invention include, for example, P-terphenyl (peak wavelength 339); BiBuQ (peak wavelength: 385); DPS (peak wavelength: 405); and Coumarin 2 (peak wavelength: 448).

In yet another embodiment the pulsed light source may be an optical parametric oscillator (OPO) pumped by another solid-state laser. OPO systems allow for a wide range of wavelength tunability in a compact system comprised entirely of solid state optical elements. The laser wavelength in OPO systems may also be varied automatically in response to user-initiated control signals or conditions encountered during use.

Catheters, useful in practicing the present invention, can take various forms. For example, one embodiment can consist of a

catheter having an outer diameter of 3.5 millimeters or less, preferably 2.5 millimeters or less. Disposed within the catheter is the optical fiber which can be a 400 micron diameter or smaller silica (fused quartz) fiber such as the model SG 800 fiber manufactured by Spectran, Inc. of Sturbridge, Mass. The catheter may be multi-lumen to provide flushing and suction ports. In one embodiment the catheter tip can be constructed of radio-opaque and heat resistant material. The radio-opaque tip can be used to locate the catheter under fluoroscopy.

The invention can be used with various catheter devices, including devices which operate under fluoroscopic guidance as well as devices which incorporate imaging systems, such as echographic or photoacoustic imaging systems or optical viewing systems. For one example of a photoacoustic imaging system which can be specifically adapted for the catheter environment, see U.S. Pat. No. 4,504,727 incorporated herein by reference.

Changes and modifications in the specifically described embodiments can be carried out without departing from the scope of the invention, which is intended to be limited by the scope of the appended claims.

THE INVENTION CLAIMED IS

1. An apparatus comprising:

a fiber optic having a proximal end and a distal end; and

an opto-acoustic transducer fixedly and operatively connected to said distal end of said fiber optic,

wherein said opto-acoustic transducer vibrates when stimulated by light propagated through said fiber optic.

2. The apparatus of claim 1, further comprising a catheter, wherein said fiber optic is located within said catheter.

3. The apparatus of claim 2, further comprising an adjunct fluid deposition tube located within said catheter, wherein said adjunct fluid deposition tube is for delivery of an adjunct fluid comprising a thrombolytic fluid or a thrombolytic agent.

4. The apparatus of claim 1, further comprising a working fluid within said opto-acoustic transducer, wherein said working fluid will expand upon absorption of light.

5. The apparatus of claim 4, wherein said working fluid is selected from a group consisting of water, saline, dyed water, blood and chloro-fluorocarbon fluid.

6. The apparatus of claim 4, wherein said working fluid comprises an inert fluid having a low critical point temperature.

7. The apparatus of claim 4, wherein said working fluid comprises an inert fluid having a low critical point temperature within the range of 250 K to 450 K.

8. The apparatus of claim 4, wherein said opto-acoustic transducer comprises:

a rigid cylinder having a first end and a second end, wherein said first end of said rigid container is fixedly connected to said distal end of said fiber optic; and

a flexible membrane fixedly connected to said second end of said rigid cylinder,

wherein said distal end of said fiber optic and said flexible membrane are sealed to said rigid cylinder to define a confined volume, wherein said flexible membrane allows expansions and contractions of said working fluid within said confined volume to be transmitted to an external medium, and

wherein said working fluid is located within said confined volume.

9. The apparatus of claim 4, wherein said opto-acoustic transducer comprises:

a rigid cylinder having a first end and a second end;

a transparent window fixedly attached to said first end, wherein said fiber optic is optically and fixedly connected to said transparent window; and

a flexible membrane fixedly connected to said second end,

wherein said transparent window and said flexible membrane are sealed to said rigid cylinder to define a confined volume, wherein said flexible membrane allows expansions and contractions of said working fluid within said confined volume to be transmitted to an external medium, and

wherein said working fluid is located within said confined volume.

10. The apparatus of claim 9, wherein said rigid cylinder has a high thermal conductivity.

11. The apparatus of claim 9, wherein said transparent window comprises a transparent dielectric material.

12. The apparatus of claim 11, wherein said transparent dielectric material is selected from a group consisting of glass, sapphire and diamond.

13. The apparatus of claim 11, wherein said transparent dielectric material comprises quartz.

14. The apparatus of claim 1, further comprising a laser to provide said light, wherein said laser produces a high repetition rate laser beam for use as an energy source for said opto-acoustic transducer.

15. The apparatus of claim 14, wherein said laser comprises a gain medium selected from a group consisting of a gaseous gain medium, a liquid gain medium and a solid state gain medium.

16. The apparatus of claim 14, wherein said laser is a rare earth-doped solid state laser.

17. The apparatus of claim 14, wherein said laser is selected from a group consisting of a ruby laser, an alexandrite laser, an Nd:YAG laser and a Ho:YLF laser.

18. The apparatus of claim 14, wherein said laser comprises means for producing harmonics of the fundamental lasing wavelength of said laser, wherein said means for producing harmonics are selected from a group consisting of a non-linear frequency-doubling crystal and a non-linear frequency-tripling crystal.

19. The apparatus of claim 2, wherein said catheter comprises a 2.5 French catheter.

20. The apparatus of claim 2, wherein said catheter comprises an endovascular catheter.

21. The apparatus of claim 4, wherein said opto-acoustic transducer comprises a bellows head, wherein said light from a laser source is absorbed by said working fluid within said bellows head, wherein said fluid vaporizes causing a pressure rise and said bellows head expands axially, impinging on an occlusion.

22. The apparatus of claim 21, wherein said bellows head comprises bio-compatible metal.

23. The apparatus of claim 22, wherein said bio-compatible metal is selected from a group consisting of platinum and gold.

24. The apparatus of claim 21, wherein said bellows comprises a non-bio-compatible metal coated with a bio-compatible metal.

25. The apparatus of claim 24, wherein said non-bio-compatible metal is selected from a group consisting of copper and nickel.

26. The apparatus of claim 21, wherein said bellows comprises a metal electroplated over a mandrel to a thickness within the range of 10 μm and 100 μm.

27. The apparatus of claim 4, wherein said opto-acoustic transducer comprises a nozzle to increase the velocity of ambient fluid flow (e.g., blood) away from the distal end of said fiber optic, wherein said nozzle provides fluid flow in the axial direction.

28. The apparatus of claim 27, further comprising at least one hole in said nozzle, wherein said ambient fluid flow is directed at an oblique angle relative to the axis of said fiber optic.

29. The apparatus of claim 27, wherein said working fluid is selected from a group consisting of water, perfused saline, dyed water, blood, chloro-fluorocarbon fluid and a thrombolytic agent.

30. The apparatus of claim 27, wherein said nozzle comprises material selected from a group consisting of metal and plastic.

31. The apparatus of claim 5, wherein said opto-acoustic transducer comprises:

a rigid cylinder having a first end and a second end; and

a suspended tip which covers said second end of said rigid container, wherein said suspended tip is fixedly connected at a point or segment of said second end such that a portion of said second end is not attached to said suspended tip,

wherein said first end of said rigid cylinder is sealed to said fiber optic, wherein said fiber optic, said rigid cylinder and said suspended tip define a confined volume,

wherein said working fluid is located within said confined volume, and

wherein a laser pulse initiates a thermodynamic cycle in said working fluid which actuates said suspended tip.

32. The apparatus of claim 31, wherein said suspended tip comprises silicon.

33. The apparatus of claim 31, wherein said suspended tip has a flat configuration.

34. The apparatus of claim 31, wherein said suspended tip comprises a shape formed thereon to increase the exertion of force by said suspended tip on a blockage.

35. The apparatus of claim 1, wherein said opto-acoustic transducer comprises a microchannel element fixedly and operatively connected to said distal end of said fiber optic.

36. The apparatus of claim 35, wherein said microchannel element comprises a first side and a second side, wherein said first side comprises fine pitched microchannels operatively and fixedly connected to said fiber optic, wherein said first side is operatively positioned to face and receive said light, wherein said second side comprises a microchannel structure having a surface area that is increased over that of a flat surface, and wherein said second side is configured to enhance the thermal transfer from said light to said working fluid.

37. The apparatus of claim 35, wherein said microchannel element comprises an anisotropically etched {110}-oriented single crystal of silicon, and wherein silicon nitride is deposited on said silicon for use as a masking layer.

38. The apparatus of claim 1, wherein said opto-acoustic transducer comprises a porous silicon element fixedly and operatively connected to said distal end of said fiber optic.

39. The apparatus of claim 9, wherein said confined volume comprises an open structure including a configuration selected from a group consisting of holes and channels.

40. The apparatus of claim 9, wherein said confined volume comprises a porous structure located within said volume to facilitate absorption of energy from said light to shorten the thermal relaxation time constant of said apparatus.

41. The apparatus of claim 9, wherein said fiber optic comprises a 400 μm diameter optical fiber and wherein said rigid cylinder comprises titanium.

42. The apparatus of claim 14, wherein said high repetition rate laser beam has a pulse frequency within the range of 10 Hz and 100 kHz.

43. The apparatus of claim 14, wherein said high repetition rate laser beam has a wavelength within the range of 200 nm and 5000 nm.

44. The apparatus of claim 14, wherein said high repetition rate laser beam has a pulse energy density within the range of 0.01 J/cm^2 to 4 J/cm^2.

45. The apparatus of claim 14, wherein said high repetition rate laser beam has a pulse duration of less than 200 ns.

46. The apparatus of claim 14, wherein said high repetition rate laser beam has a sinusoidal pulse waveform.

47. The apparatus of claim 14, wherein said high repetition rate laser beam has a pulse duration that is less than 1 μs.

48. The apparatus of claim 14, wherein said high repetition rate laser beam has (i) a pulse frequency within the range of 10 Hz to 100 kHz, (ii) a wavelength within the range of 200 nm to 5000 nm, (iii) a pulse energy density within the range of 0.01 J/cm^2 to 4 J/cm^2 and (iv) a pulse duration of less than 200 ns.

49. The apparatus of claim 14, wherein said high repetition rate laser beam comprises (i) a pulse frequency within the range of 10 Hz to 100 kHz, (ii) a wavelength within the range of 200 nm to 5000 nm, (iii) a pulse energy density within the range of 0.01 J/cm^2 to 4 J/cm^2 and (iv) a sinusoidal pulse waveform.

50. The apparatus of claim 14, wherein said high repetition rate laser beam has (i) a pulse frequency within the range of 10 Hz to 100 kHz, (ii) a wavelength within the range of 200 nm to 5000 nm, (iii) a pulse energy density within the range of 0.01 J/cm^2 to 4 J/cm^2 and (iv) a pulse duration that is less than 1 μs.

51. A method for removing a vascular occlusion, comprising:

inserting a catheter into a blood vessel, wherein said catheter comprises:

a fiber optic having a proximal end and a distal end; and

an opto-acoustic transducer fixedly and operatively connected to said distal end of said fiber optic, wherein said opto-acoustic transducer comprises a working fluid, wherein said opto-acoustic transducer vibrates when stimulated by light propagated through said fiber optic; and

said method further comprising coupling a high repetition rate laser beam into said fiber, wherein said beam is absorbed by said working fluid, wherein said transducer generates acoustic waves to remove a vascular occlusion within said blood vessel.

52. The method of claim 51, wherein said high repetition rate laser beam has a pulse frequency within the range of 10 Hz to 100 kHz.

53. The method of claim 51, wherein said high repetition rate laser beam has a wavelength within the range of 200 nm to 5000 nm.

54. The method of claim 51, wherein said high repetition rate laser beam has a pulse energy density within the range of 0.01 J/cm^2 to 4 J/cm^2.

55. The method of claim 51, wherein said high repetition rate laser beam has a pulse duration of less than 200 ns.

56. The method of claim 51, wherein said high repetition rate laser beam has a pulse duration that is sinusoidal.

57. The method of claim 51, wherein said high repetition rate laser beam has a pulse duration that is less than 1 μs.

58. The method of claim 51, wherein said high repetition rate laser beam has (i) a pulse frequency within the range of 10 Hz to 100 kHz, (ii) a wavelength within the range of 200 nm to 5000 nm, (iii) a pulse energy density within the range of 0.01 J/cm^2 to 4 J/cm^2 and (iv) a pulse duration of less than 200 ns.

59. The method of claim 51, wherein said high repetition rate laser beam has (i) a pulse frequency within the range of 10 Hz to 100 kHz, (ii) a wavelength within the range of 200 nm to 5000 nm, (iii) a pulse energy within the range of 0.01 J/cm^2 to 4 J/cm^2 and (iv) a sinusoidal pulse waveform.

60. The method of claim 51, wherein said high repetition rate laser beam has (i) a pulse frequency within the range of 10 Hz to 100 kHz, (ii) a wavelength within the range of 200 nm to 5000 nm, (iii) a pulse energy density within the range of 0.01 J/cm^2 to 4 J/cm^2 and (iv) a pulse duration that is less than 1 μs.

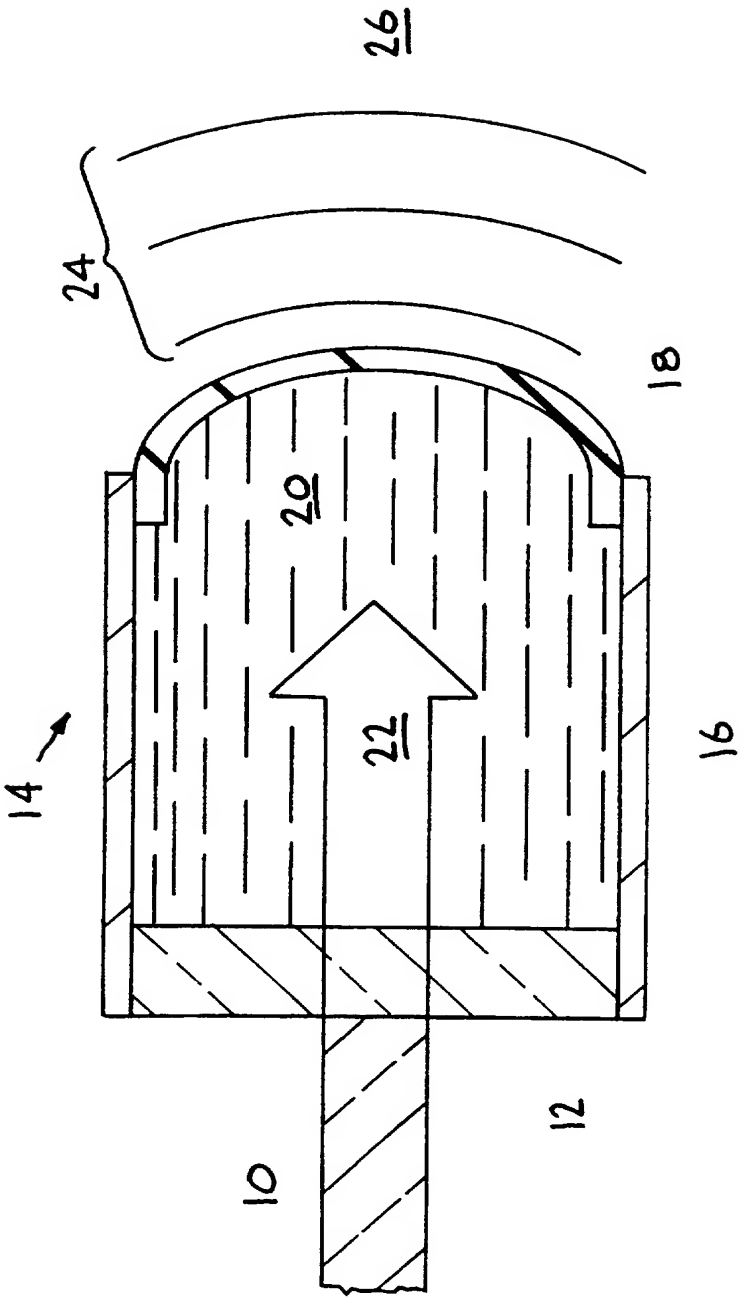
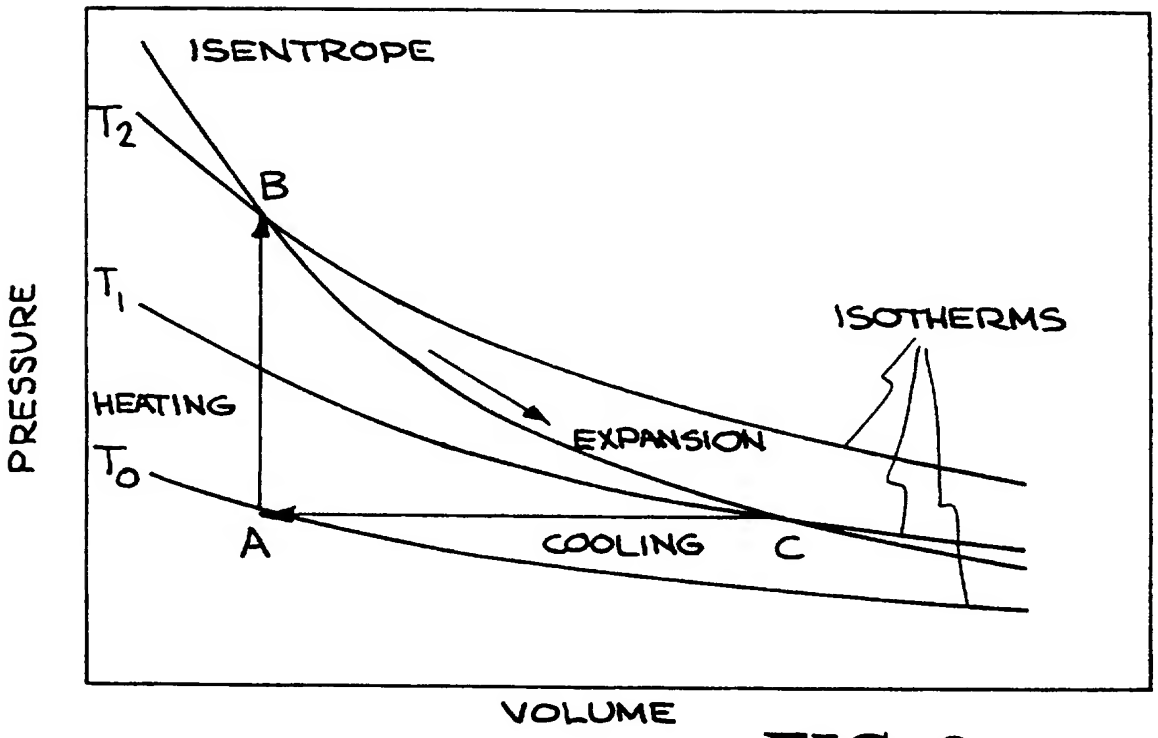


FIG. 1


ISENTROPE
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B
T_1
ISOTHERMS
PRESSURE
HEATING
EXPANSION
T_0
A
COOLING
C
VOLUME

FIG. 2

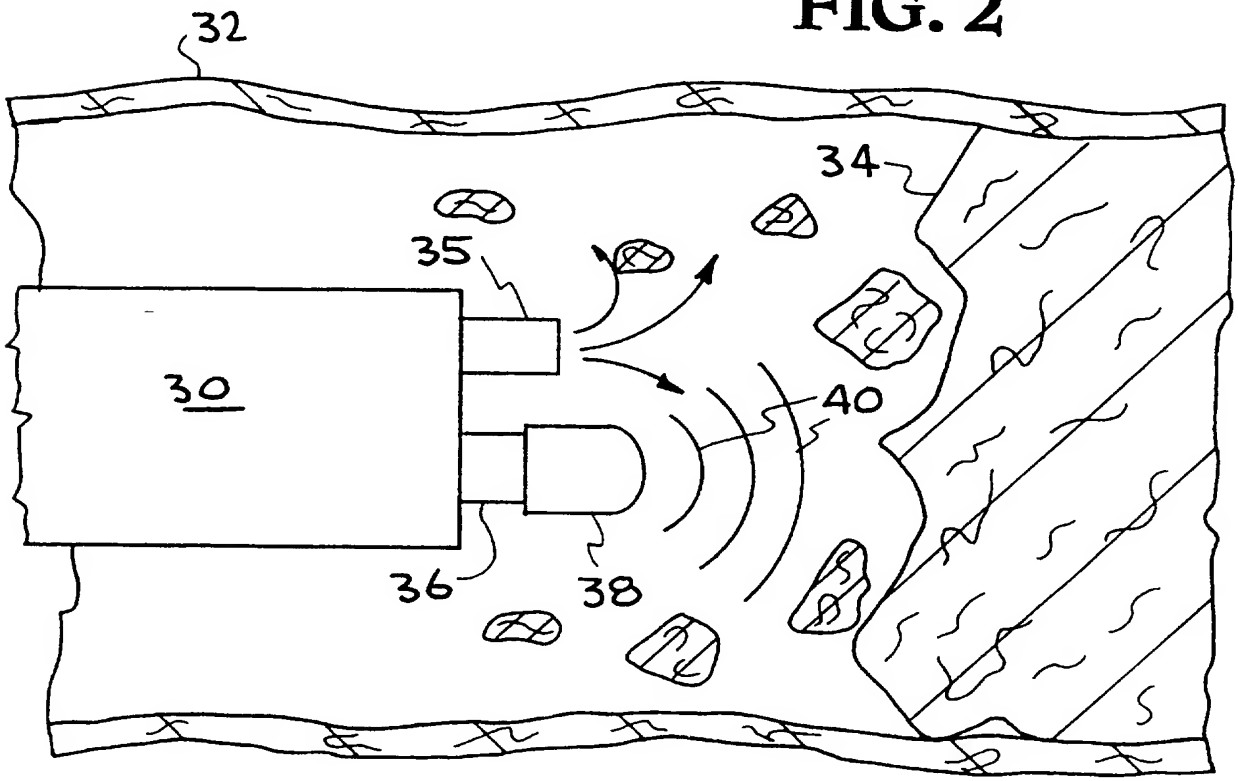
32
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FIG. 3

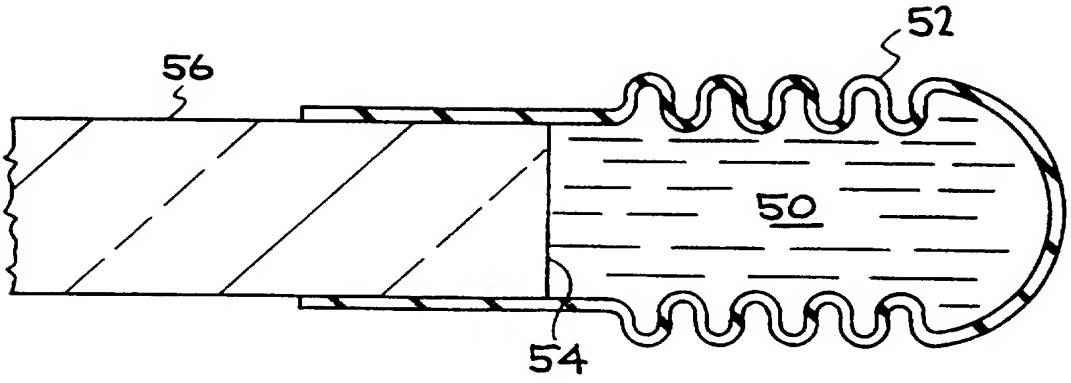

FIG. 4

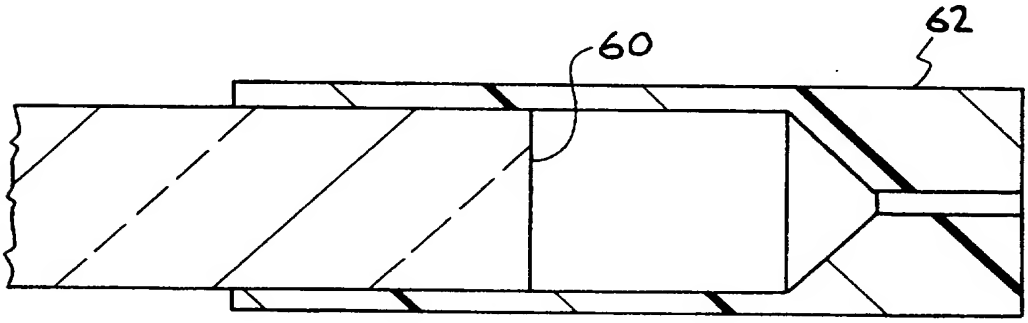

FIG. 5

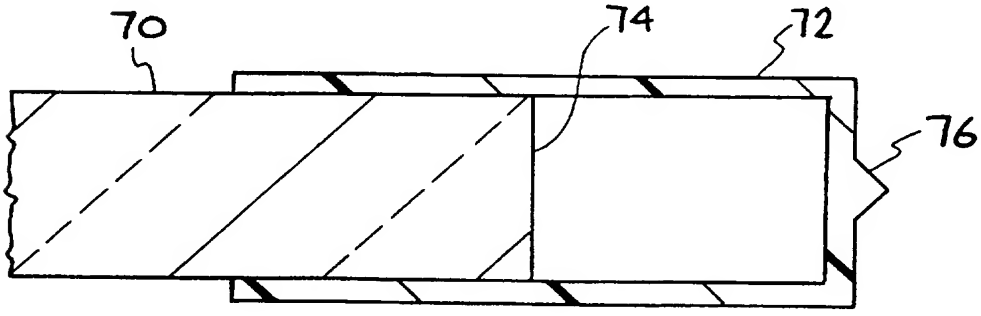

FIG. 6

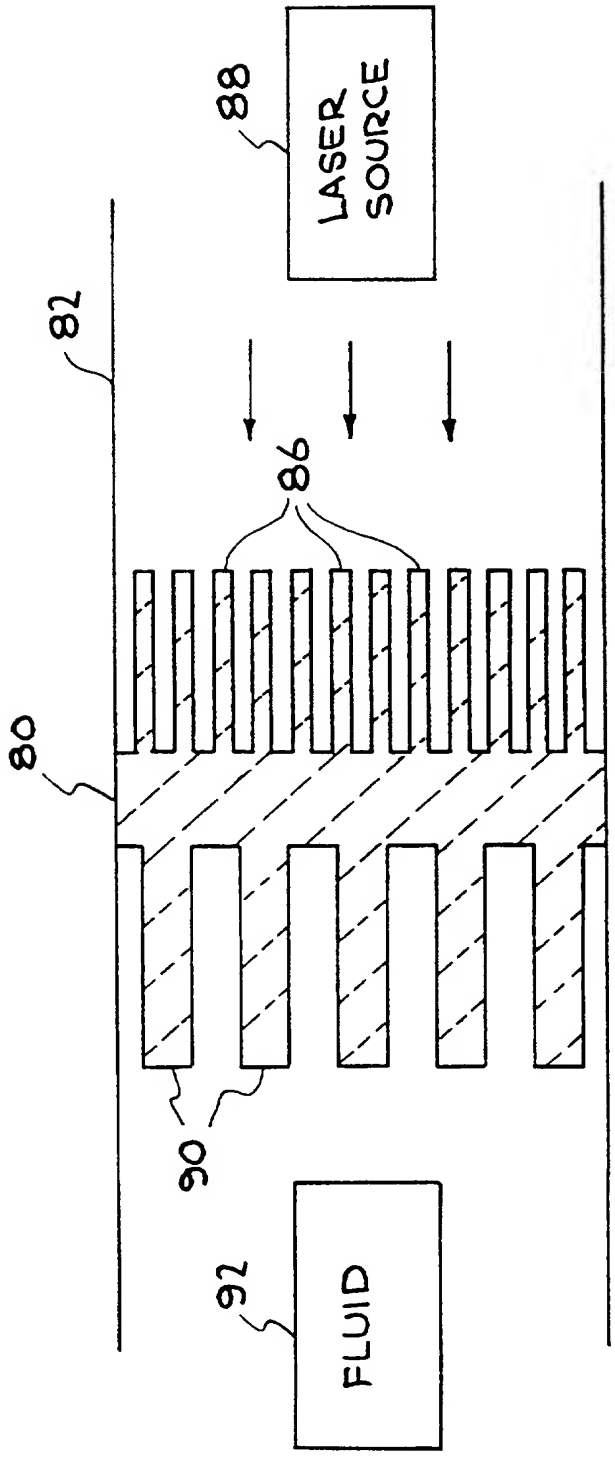

FIG. 7

INTERNATIONAL SEARCH REPORT

Inter. nal Application No
PCT/US 97/06867

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 A61B17/36

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 A61B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	WO 91 10403 A (CANDELA LASER CORP.) 25 July 1991 see page 4, line 14 - page 7, line 6 see page 8, line 17 - line 19	1,2,4,5 3,6-50
X Y	EP 0 571 306 A (LEVY) 24 November 1993 see column 2, line 58 - column 3, line 13 see column 4, line 7 - line 11 see column 4, line 27 - line 33	1,2,4,5 6-50
X	WO 90 09762 A (ROSEN ET AL.) 7 September 1990 see page 5, line 13 - line 22	1,2,14, 17
X A	WO 91 11963 A (UNIVERSITE DE NICE-SOPHIA ANTIPOLIS) 22 August 1991 see claims 1,10,14	1,2 3
	-/--	

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
11 September 1997	18. 09. 97

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+ 31-70) 340-2040, Tx. 31 651 epo nl, Fax (+ 31-70) 340-3016	Glas, J

Form PCT/ISA/210 (second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

Inten nal Application No
PCT/US 97/06867

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 90 12544 A (KARL STORZ) 1 November 1990 see claims 6,10	1,2,14, 17,18
X	WO 93 11711 A (PSI MEDICAL PRODUCTS, INC.) 24 June 1993 see page 6, line 14 - line 23 see page 9, line 28 - line 34	1,2,4,5, 14,17, 31,33,34
Y	WO 92 06739 A (THE GENERAL HOSPITAL CORPORATION) 30 April 1992 see page 12, line 8 - line 12	3
A	US 5 342 355 A (LONG) 30 August 1994 see column 7, line 66 - column 8, line 4 see column 14, line 30 - line 36	1,4,8-10

2

INTERNATIONAL SEARCH REPORT

I. .national application No.

PCT/US 97/ 06867

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. [X] Claims Nos.: 51-60
because they relate to subject matter not required to be searched by this Authority, namely:
PCT Rule 39.1(iv) Method for treatment of the human or animal body by surgery

2. [ ] Claims Nos.:
because they relate to parts of the International Application that do not comply with the prescribed requirements to such an extent that no meaningful International Search can be carried out, specifically:

3. [ ] Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. [ ] As all required additional search fees were timely paid by the applicant, this International Search Report covers all searchable claims.

2. [ ] As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. [ ] As only some of the required additional search fees were timely paid by the applicant, this International Search Report covers only those claims for which fees were paid, specifically claims Nos.:

4. [ ] No required additional search fees were timely paid by the applicant. Consequently, this International Search Report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

[ ] The additional search fees were accompanied by the applicant's protest.

[ ] No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

Information on patent family members

Intern ial Application No
PCT/US 97/06867 -

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Information on patent family members

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